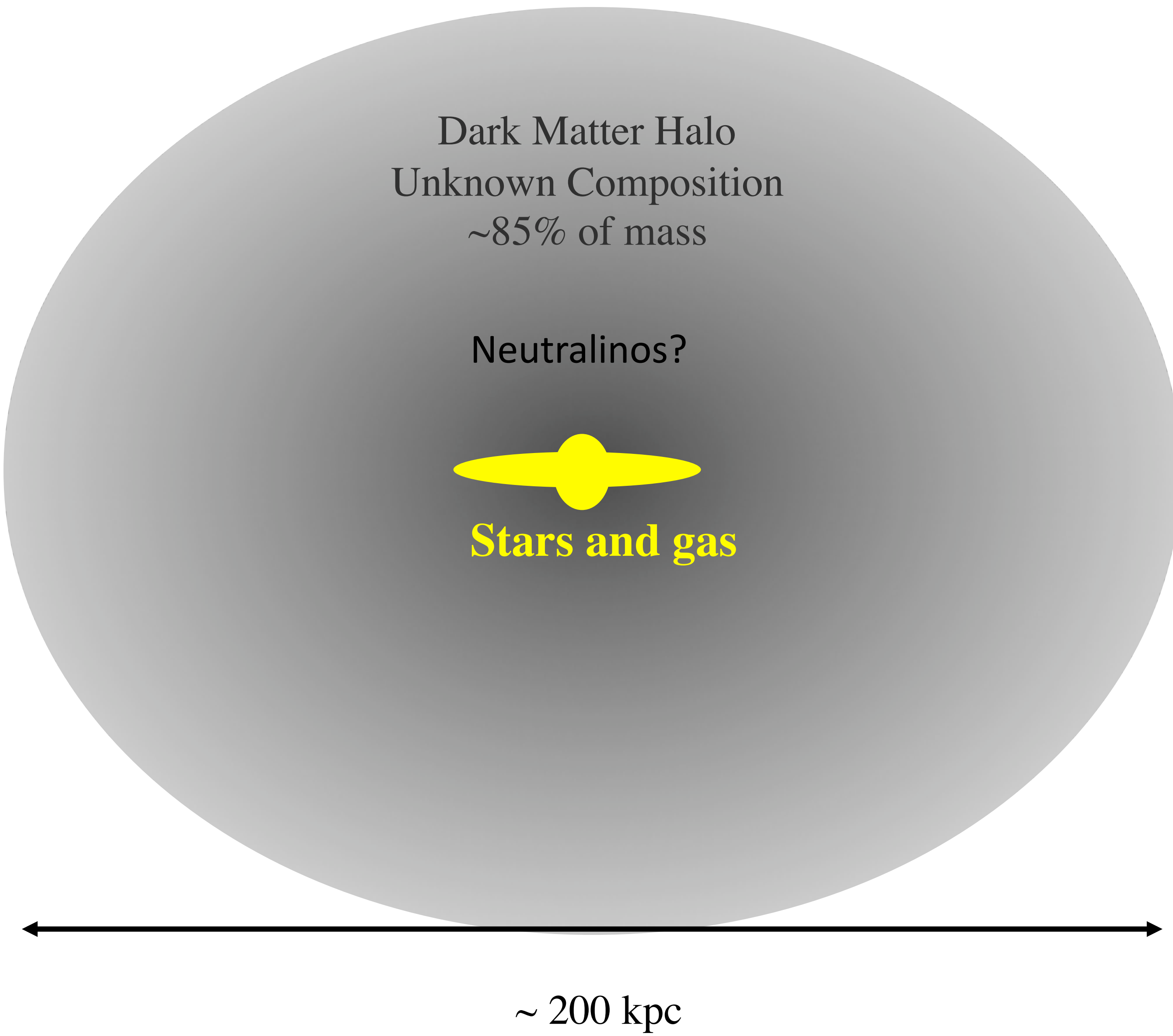
Dark Matter Detection

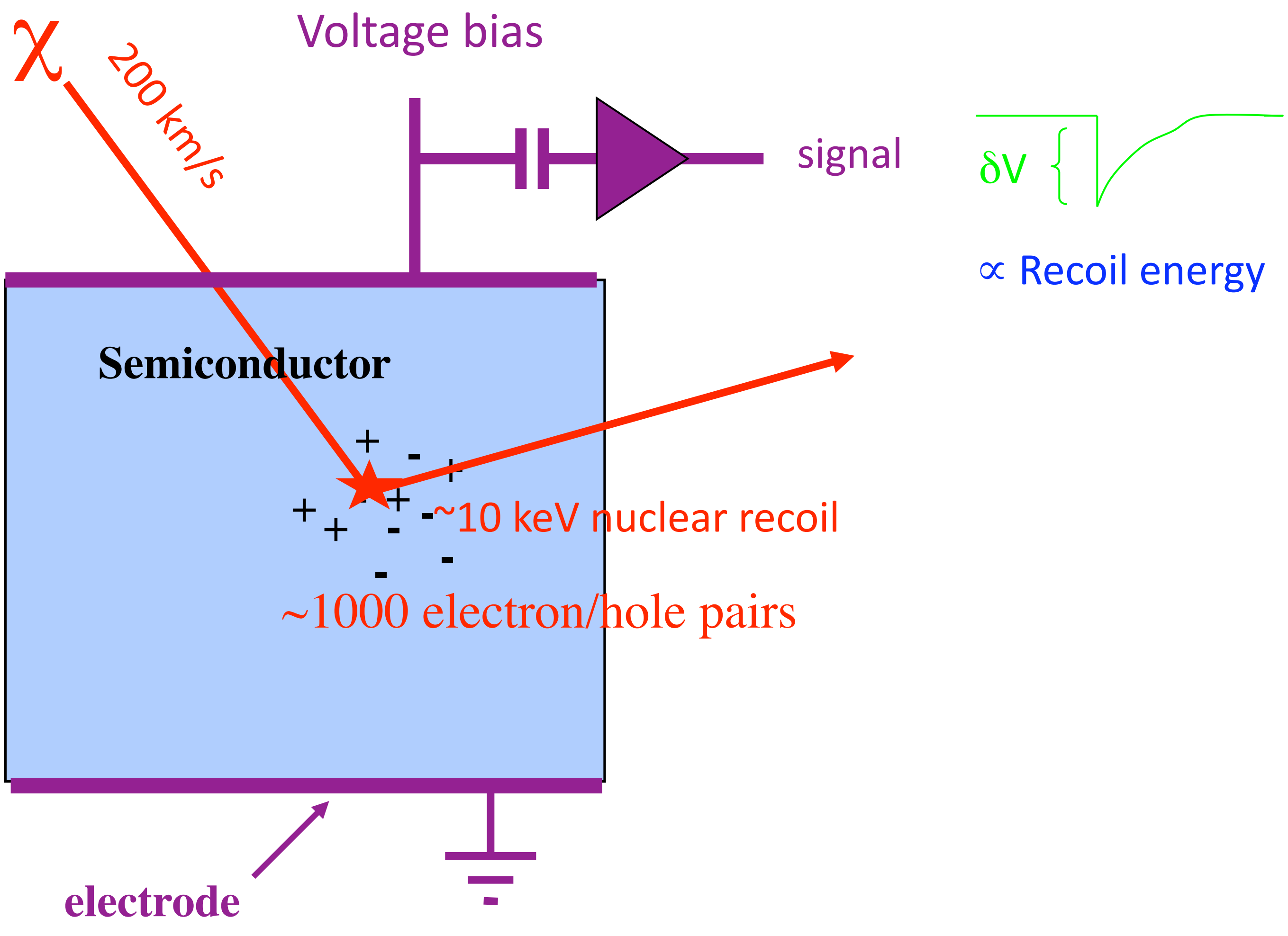
Andrew Sonnenschein

Fermilab Users Meeting,
June 4, 2009

Cartoon of a Galaxy



Generic 1st Generation WIMP Detection Experiment
ca 1987

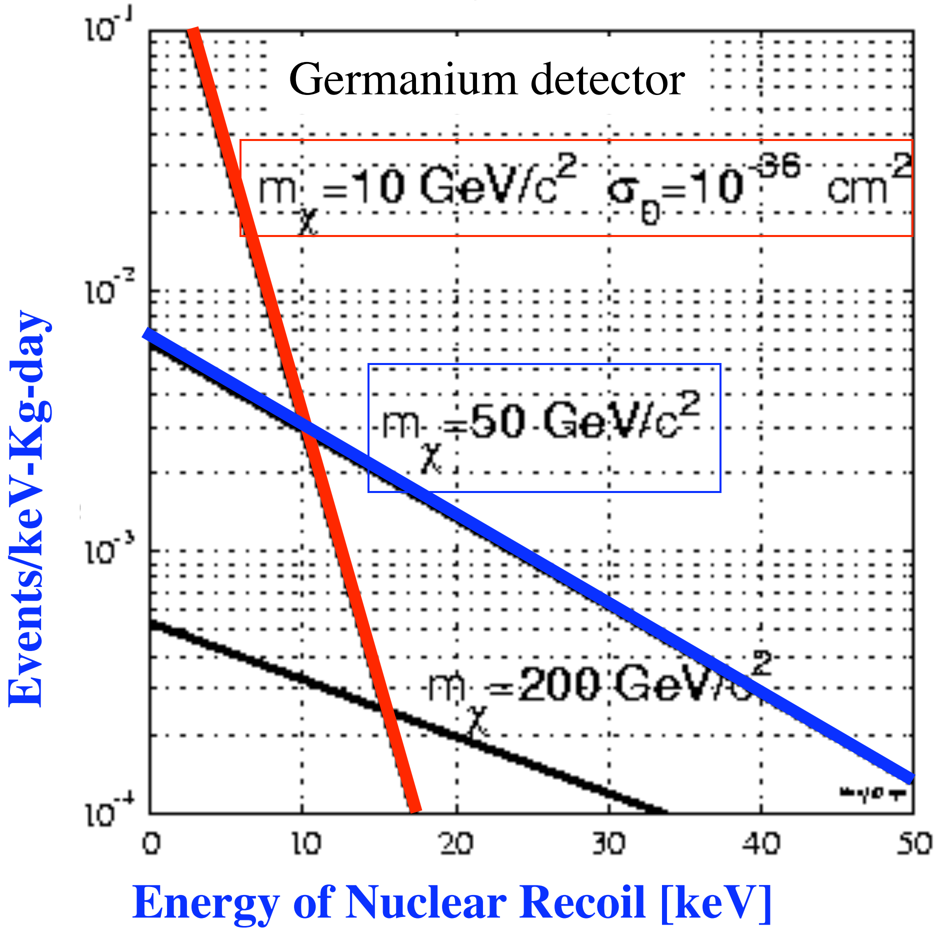


Spectrum of WIMPs in a Detector on Earth

Based on simple assumptions:

- Particles are gravitationally bound to halo, with Maxwellian velocity distribution (V_{rms}=220 Km/s) and local density 0.3 GeV/cm^3
- WIMPs are heavy particles, 10 GeV< M_{WIMP}< 1 TeV.

➡ Nuclear scattering can efficiently transfer energy to a nucleus, since $M_{nucleus}$~M_{wimp}. The signal will be a nuclear recoil, with energy ~10 keV



- Scattering is non-relativistic.
- Shape of spectrum does not depend on particle physics inputs.
- Amplitude of spectrum depends on unknown supersymmetry parameters and some astrophysical uncertainties.

The Experimental Challenge

- Energy transferred by WIMP to a target nucleus is low.
  - ~10 keV, similar to an X-ray
  - Recoil track has a length of only ~100 nm in a solid material

- Event rate is low.
  - Cross sections for nuclear scattering $<10^{-43}$ cm^2
  - Implies < 0.01 events per kg of target per day

- Backgrounds from environmental radioactivity are high.
  - Trace levels of radioactive isotopes in environment and detector construction materials.
  - ~10^2/kg-day with state-of-the-art shielding
  - Most of these events are due to scattering on electrons (Compton, photoelectric scattering), while the signal is a nuclear recoil.

=> We need to build detectors which discriminate between nuclear and electron scattering at low energy, over large target volumes.

CDMS Collaboration

<u>CDMS Institutions</u>

DOE Laboratory

Fermilab

NIST

DOE University

CalTech

Florida

Minnesota

MIT

Stanford

UC Santa Barbara

NSF

Case Western

Colorado (Denver)

Santa Clara

UC Berkeley

Syracuse

Canada

Queens

Fermilab Personnel: Dan Bauer (Project Manager), Fritz DeJongh, Erik Ramberg, Jonghee Yoo, Jeter Hall, Lauren Hsu, Sten Hansen, Rich Schmitt

CDMS Detectors: Background Rejection Though Simultaneous Measurement of Phonons and Ionization

Use charge/phonon AND phonon timing

Measured background rejection:

99.9998% for γ's, 99.79% for β's

Clean nuclear recoil selection with ~ 50% efficiency

Tower of 6 ZIPs

Tower 1

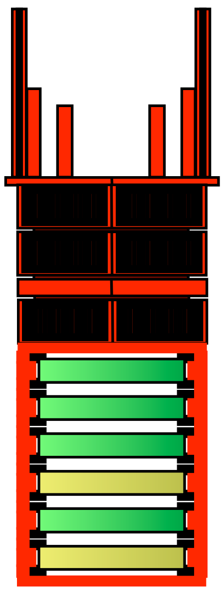
4 Ge

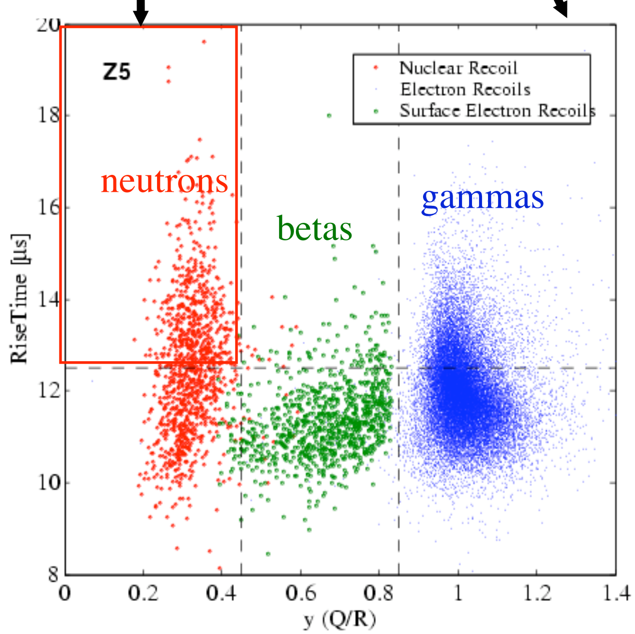
2 Si

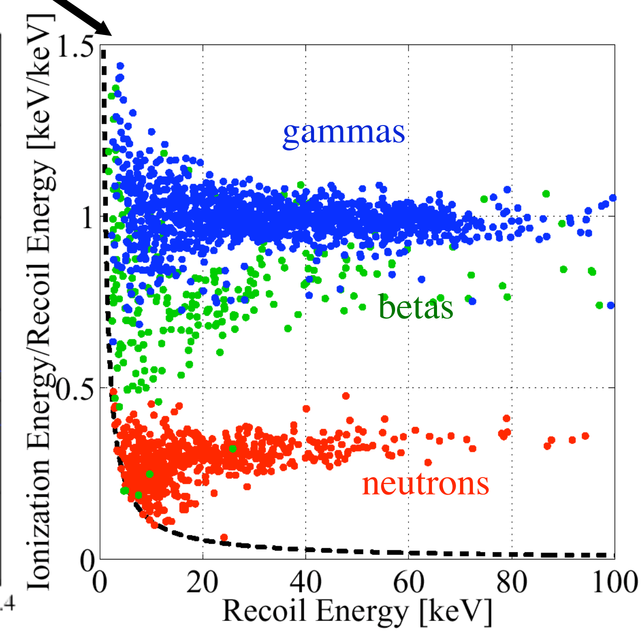
Tower 2

2 Ge

4 Si

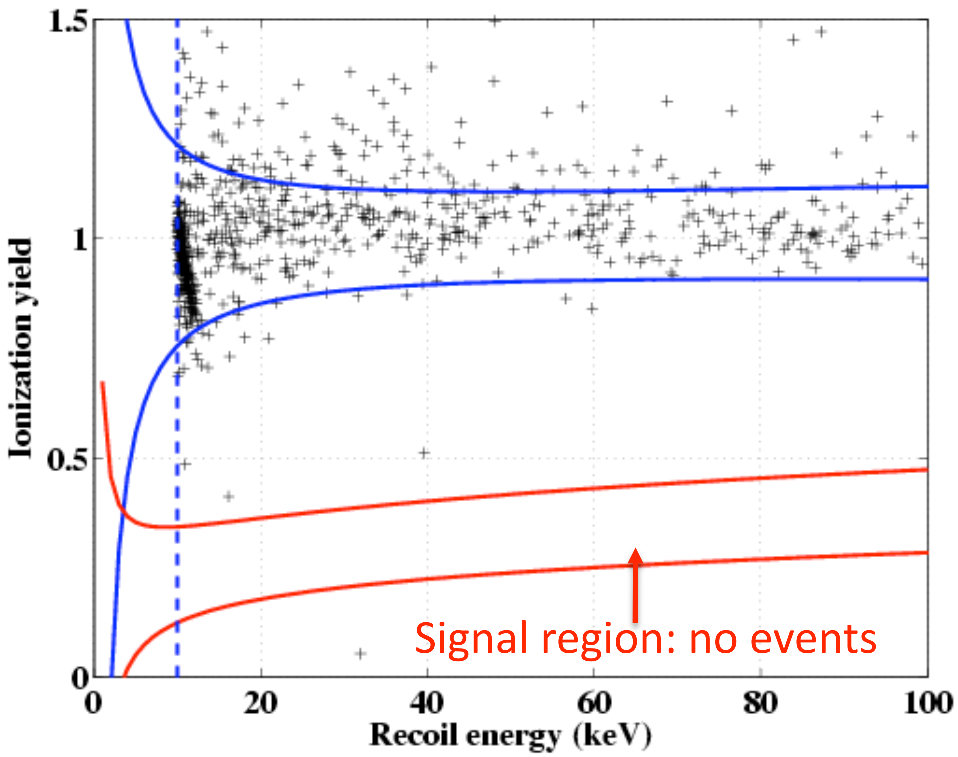


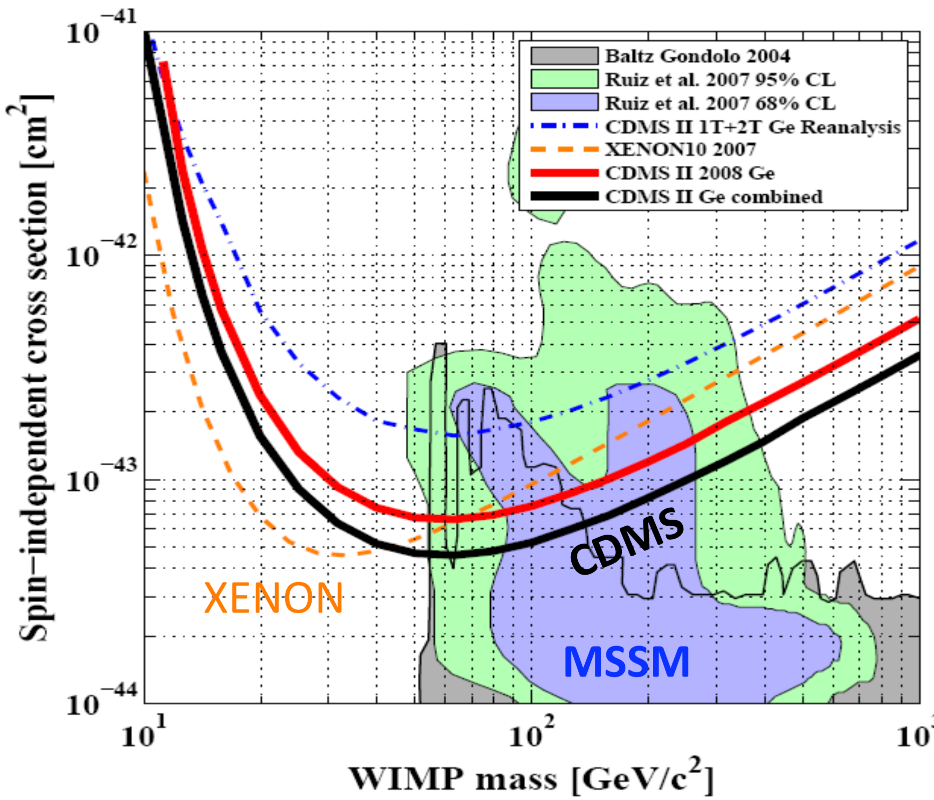




CDMS Spin-Independent Sensitivity

- Most recent result: Feb. 2008, 650 kg-days (121 kg-days after cuts)
- Expecting another factor of 2-3 improvement in sensitivity this summer from data already collected.





New, More Massive CDMS Detectors

• New detectors: 2.5 cm thick (600 g) instead of 1 cm.

• Detector optimization: full wafer lithography & better tungsten target improve yield, reducing need for testing and repairs.

• Supertowers: 5 dark matter detectors plus 2 thin endcap veto detectors. Each supertower will have fiducial mass equivalent to previous 5-tower array.

• Two supertowers are funded and first was installed in April.

• Have proposed 5-tower upgrade for Soudan.

⇒16 kg germanium target mass by 2011

Decision expected this summer by DOE & NSF

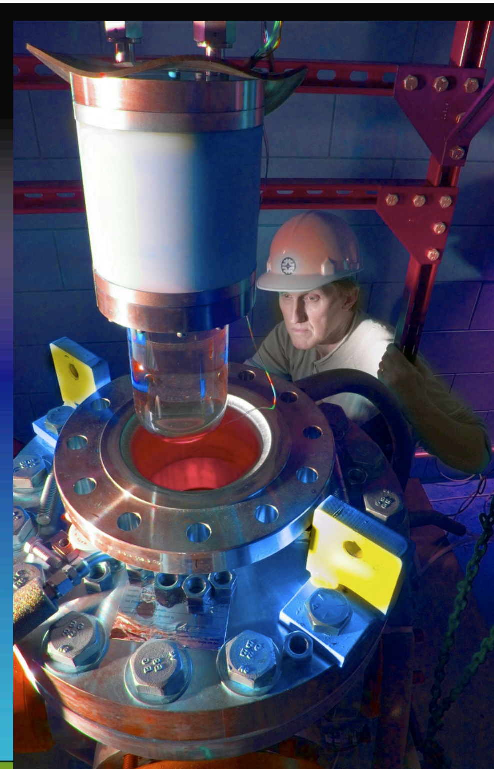
First 3-kg supertower

COUPP

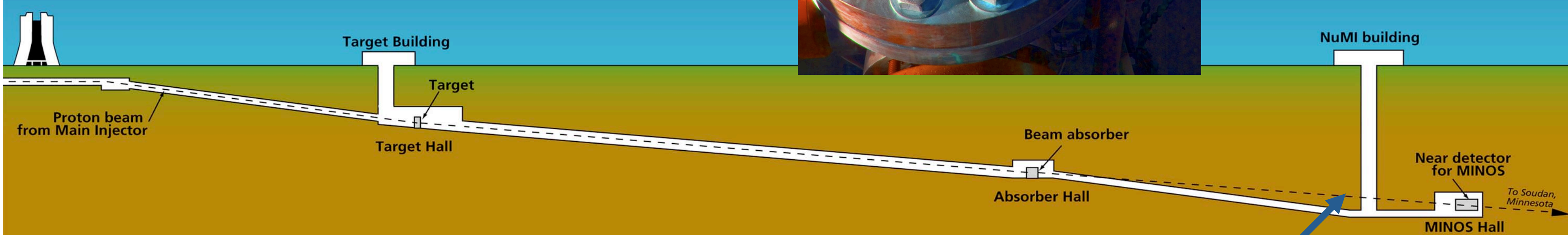
University of Chicago

Indiana University, South Bend

Fermilab

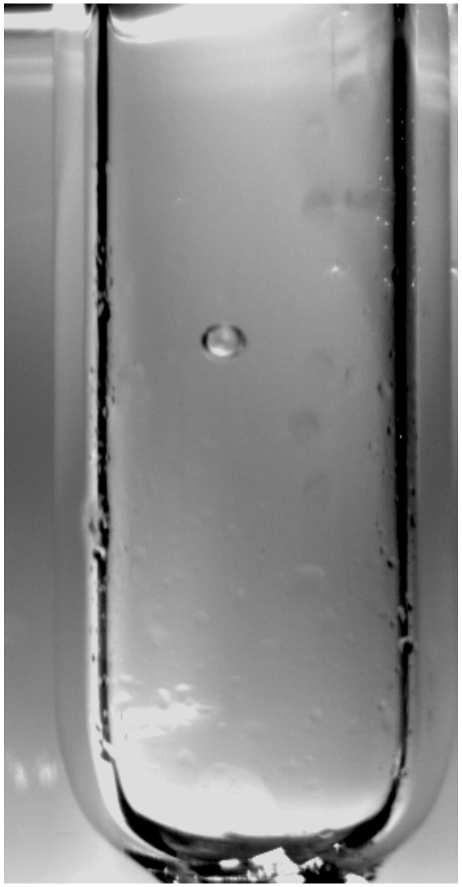


1 liter (2 kg) Bubble Chamber In NuMI tunnel



test site
~300 m.w.e.

Why Bubble Chambers?



1. **Large target masses would be possible.**
    - Multi ton chambers were built in the 50's- 80's.
2. **An exciting menu of available target nuclei.**

***No liquid that has been tested seriously has failed to work as a bubble chamber liquid* (Glaser, 1960).**

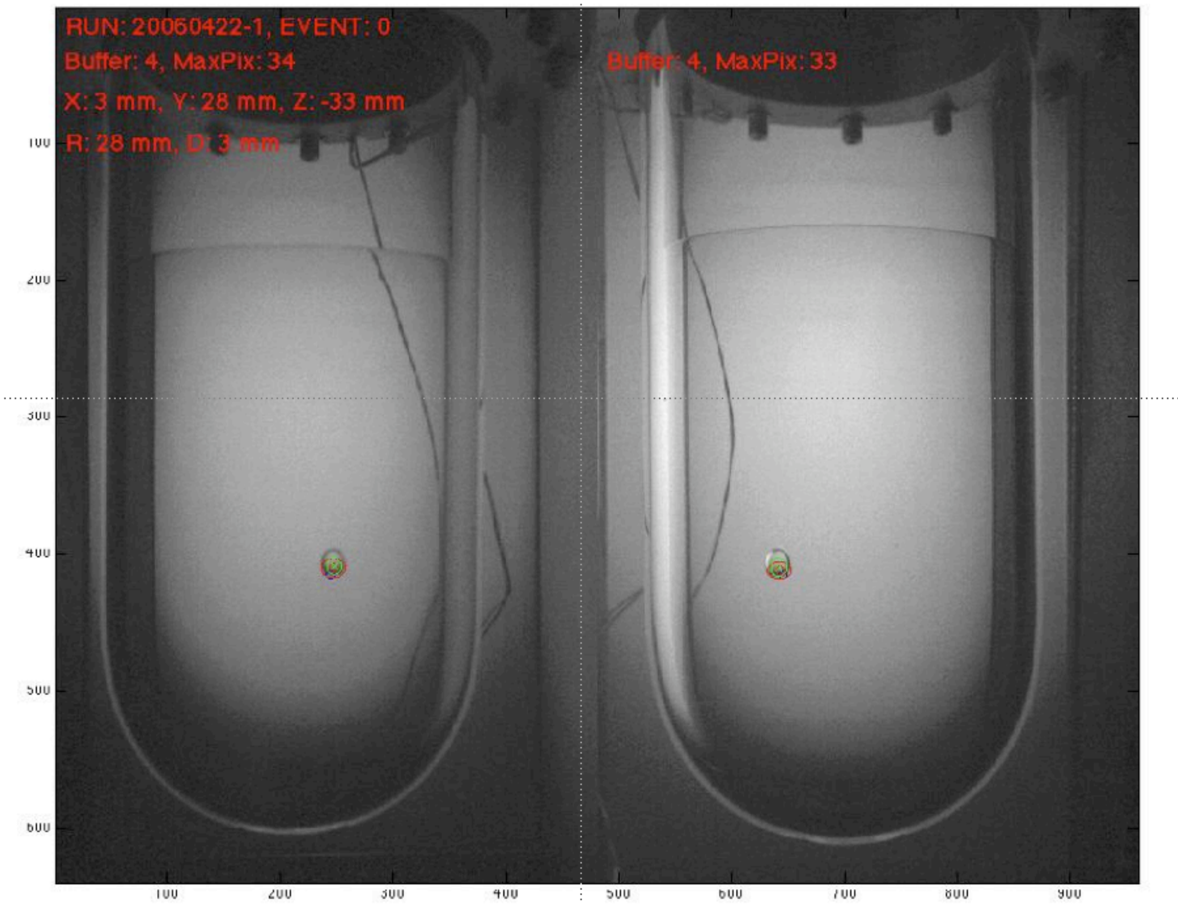
- Most common: Hydrogen, Propane
- But also "Heavy Liquids": Xe, Ne, CF_3Br, CH_3I, and CCl_2F_2.
- Good targets for both spin- dependent and spin-independent scattering.
- Possible to "swap" liquids to check suspicious signals.

3. Backgrounds due to environmental gamma and beta activity can be suppressed by running at low pressure.

- Bubble nucleation depends on dE/dx, which is low for electrons, high for nuclear recoils

A Typical COUPP Event

Two views of same bubble (cameras offset by 90°):



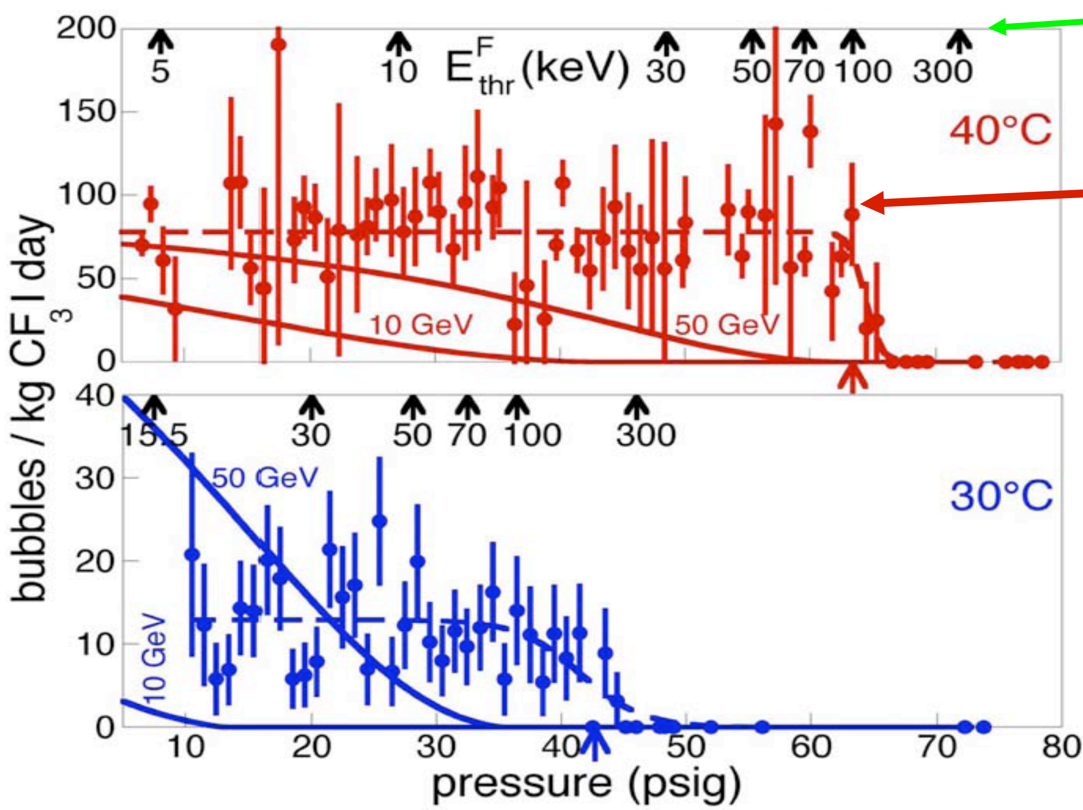
A WIMP interaction would produce a single bubble (no tracks or multiples)

Appearance of a bubble causes the chamber to be triggered by image processing software.

Bubble positions are measured in three dimensions from stereo camera views

Data from 2006 Run

- Data from pressure scan at two temperatures.
- Fit to alphas + WIMPs



Energy Threshold
In KeV

Radon
background

Solid lines:
Expected WIMP

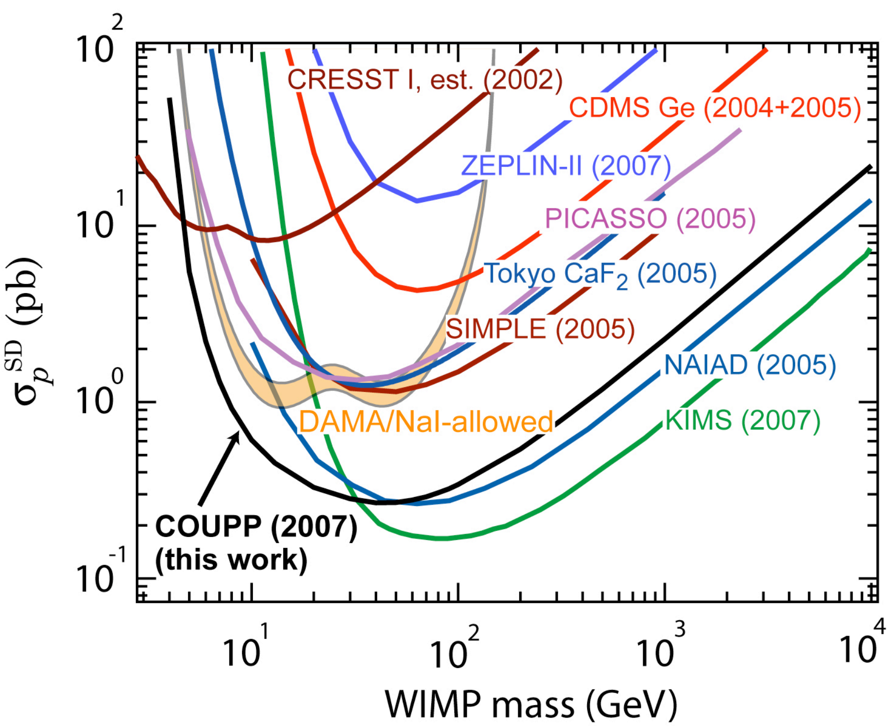
response for

$\sigma^{SD(p)}$=3 pb

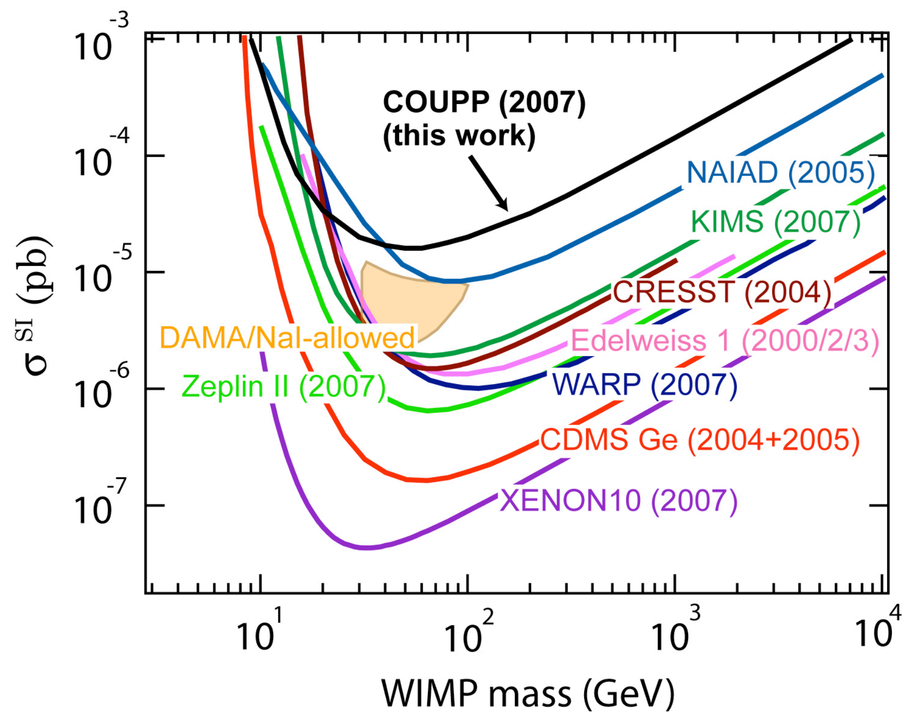
COUPP: First Results

- We have competitive sensitivity for spin-dependent scattering, despite high radon background in 200-2007 runs of 2-kg chamber.

Spin-dependent



Spin-independent

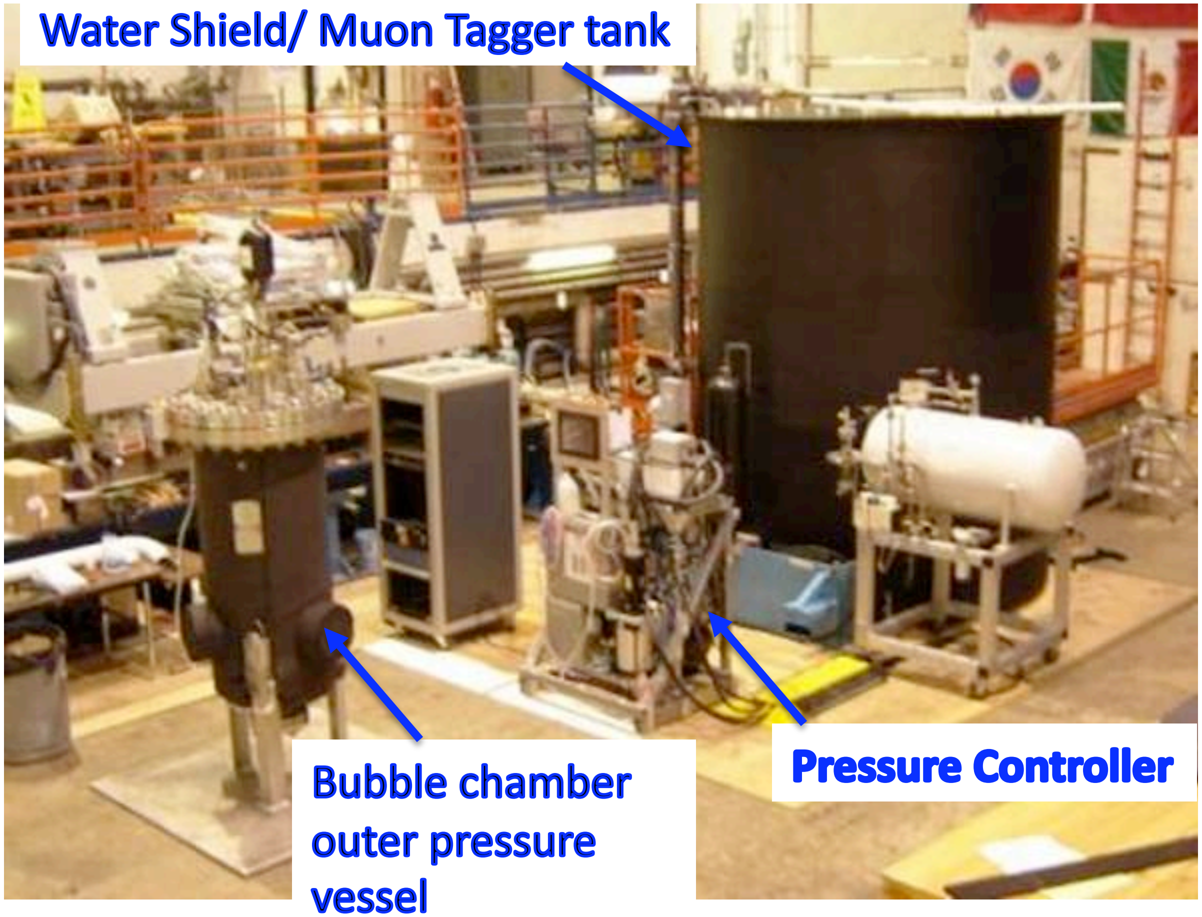


Science, 319: 933-936 (2008).

COUPP 60-kg Chamber (Fermilab E-961)

- More than 30 times larger target volume than previous device.
- High purity materials and fluid handling systems based on solar neutrino detector technology--- goal is to reduce alpha-emitter backgrounds by three orders of magnitude.

Bubble chamber Inner Vessel

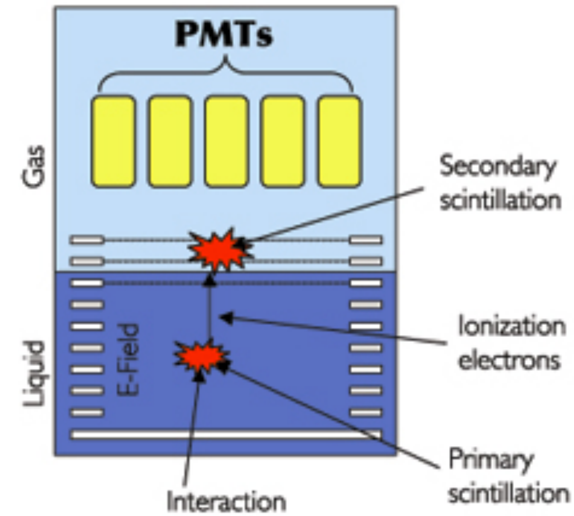


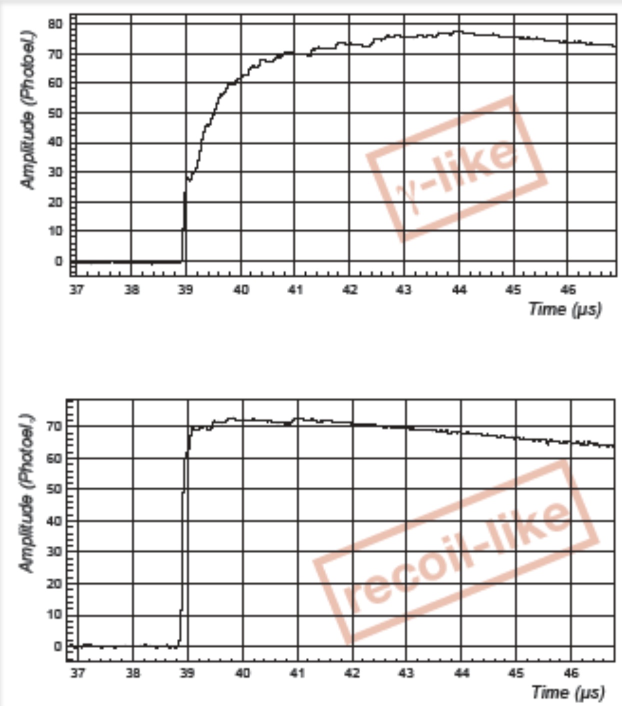
Summary: Current Dark Matter Experiments with Fermilab Participation

- CDMS
  - Leading spin-independent sensitivity over most of mass range.
  - Expecting to release new result this summer- x 3 sensitivity.
  - First 3-kg “supertower” installed in Soudan.
  - Detector costs are coming down rapidly, due to larger crystals, more efficient processing.
- COUPP
  - Leading spin-dependent WIMP-proton sensitivity below 30 GeV.
  - 60-kg detector is nearing completion
  - Backgrounds from alpha decay expected to decrease with use of higher purity materials, better fluid handling.

The Competition: Argon and Xenon TPCs

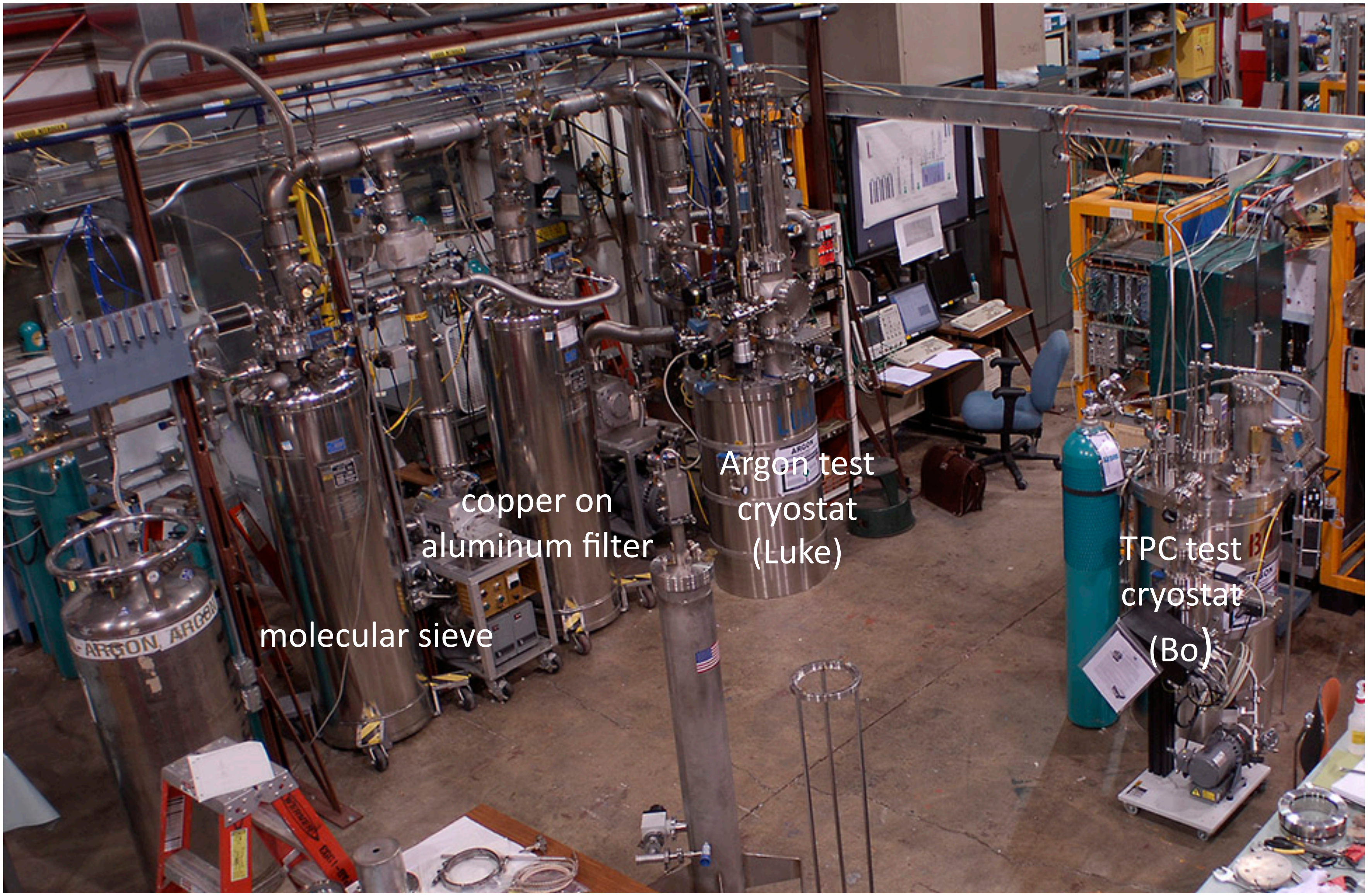
- Measure scintillation and ionization in a large volume of condensed noble gas.
- Xenon-100 kg and WARP- 140 kg (Argon) detectors are now running at Gran Sasso, will quickly take lead in sensitivity if they reach design performance goals.
- Xenon advantages
  - large cross section (A^2) enhancement for coherent WIMP-nucleus scattering.
  - Efficient self-shielding, due to high density of liquid xenon.
  - No long-lived radioactive xenon isotopes
- Argon advantages
  - Much higher background discrimination power due to discrepancy in scintillation decay times for signal vs. background events.
  - Less expensive; available in large quantities





Pulse shape discrimination in argon (WARP)

Fermilab Liquid Argon Detector Infrastructure



I. THE MAX COLLABORATION

Arizona State University, USA Prof. Ricardo Alarcon, Septimiu Balascuta
Augustana College, USA Prof. Drew Alton
Black Hills State University, USA Prof. Dan Durben, Prof. Kara Keeter, Prof. Michael Zehfus
Columbia University, USA Prof. Elena Aprile, Dr. Karl-Ludwig Giboni, Dr. Tom Haruyama, Dr. Rafael Lang, Dr. Antonio Jesus Melgarejo, Dr. Kaixuan Ni, Guillaume Plante, Bin Choi, Kyungeun Elizabeth Lim, Taehyun Yoon, Dr. Gordon Tajiri
Fermi National Accelerator Laboratory, USA Dr. Steve Brice, Dr. Aaron Chou, Pierre Gratia, Dr. Jeter Hall, Dr. Stephen Pordes, Dr. Andrew Sonnenschein
INFN, Laboratori Nazionali del Gran Sasso, Italy Dr. Francesco Arneodo, Serena Fattori, Dr. Walter Fulgione
Massachusetts Institute of Technology, USA Prof. Jocelyn Monroe
Princeton University, USA Alvaro Chavarria, Ernst de Haas, Prof. Cristiano Galbiati, Victor Garzotto, Augusto Goretti, Andrea Ianni, Tristen Hohman, Ben Loer, Prof. Peter Meyers, David Montanari, Allan Nelson, Marc Osherson, Eng. Robert Parsells, Richard Saldanha, Eng. William Sands
Rice University, USA Prof. Uwe Oberlack, Yuan Mei, Marc Schumann, Peter Shagin
Temple University, USA Prof. Jeff Martoff, Prof. Susan Jansen-Varnum
University of California at Los Angeles, USA Daniel Aharoni, Prof. Katsushi Arisaka, Ethan Brown, Prof. David Cline, Jonathan Kubic, Dr. Emilija Pantic, Prof. Peter F. Smith, Artin Teymourian, Chi Wai Lam, Dr. Hanguo Wang
University of Coimbra, Portugal Dr. Joao Cardoso, Luís Carlos Costa Coelho, Prof. Joaquim Marques Ferreira dos Santos, Prof. José António Matias Lopes, Dr. Sonja Orrigo, Antonio Ribeiro
University of Houston, USA Prof. Ed Hungerford and Prof. Lawrence Pinsky
University of Massachusetts at Amherst, USA Prof. Andrea Pocar
University of Muenster, Germany Dr. Marcus Beck, Dr. Volker Hannen, Karen Hugenberg, Dr. Hans-Werner Ortjoahnn, Prof. Christian Weinheimer
University of Notre Dame, USA Prof. Philippe Collon, Daniel Robertson, Christopher Schmitt
University of Virginia, USA Prof. Kevin Lehmann
University of Zürich, Switzerland Ali Askin, Prof. Laura Baudis, Dr. Alfredo Ferella, Marijke Haffke, Alexander Kish, Dr. Roberto Santorelli, Dr. Eirini Tziaferi
Waseda University, Japan Prof. Tadayoshi Doke, Prof. Nobuyuki Hasebe, Mitsuteru Mimura, Dr. Mitsuhiro Miyajima, Dr. Shinichi Sasaki, Dr. Satoshi Suzuki, Prof. Shoji Torii

MAX Collaboration

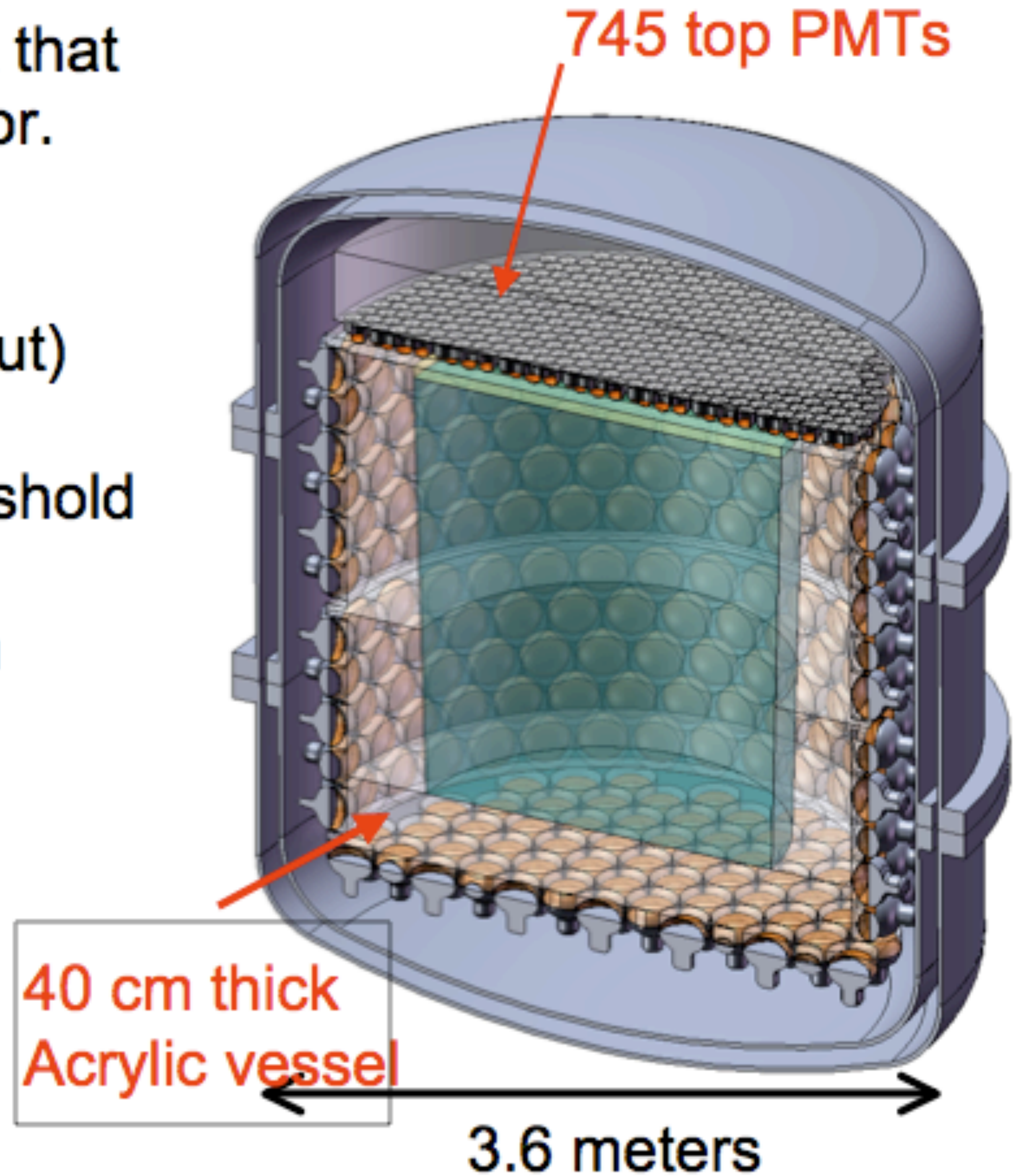
90 people
19 institutions

- DUSEL Proposal: Coordinated preliminary design of multi-ton argon and xenon TPCs.

- Includes participants in WARP, Xenon-100 + others

Argon Detector Concept

- Largest diameter cryostat that will fit down DUSEL elevator.
- 5 tons depleted argon
  (2.6 tons after fiducial cut)
- 30 keV recoil energy threshold
- ~ 2 cm position resolution
- 0.5 background events expected in 5-year run.



3 order of magnitude improvement over present CDMS/ XENON sensitivity

Proposals for Dark Matter Experiments at DUSEL

- The Preliminary Design (NSF S4 Solicitation) proposals show what the community thinks will be possible on a 10-year time scale.
- Each proposal aims to achieve negligible background rates for target masses of 1 ton or more.
- Fermilab scientists are involved in three of these so far (indicated in red).

Technology	Experiment	Target	Mass (T)	Cost (M$)
Low temperature Ionization/Phonon	GEODM	Germanium	1.5	50
Bubble Chamber	COUPP	Fluorine, Iodine	n* 0.5	n*0.5
Liquid Argon/Neon Scintillator	CLEAN-40T	Argon Neon	40	40
Dual Phase TPC	LZ20	Xenon	20?	100?
	MAX	Argon Xenon	5 2	17 18
Gas TPC	DRIFT	Fluorine Sulfur	1	60

Summary

- Presently, Fermilab supports two of the most sensitive experiments, CDMS and COUPP. Both are expected to achieve large sensitivity improvements in the next year.

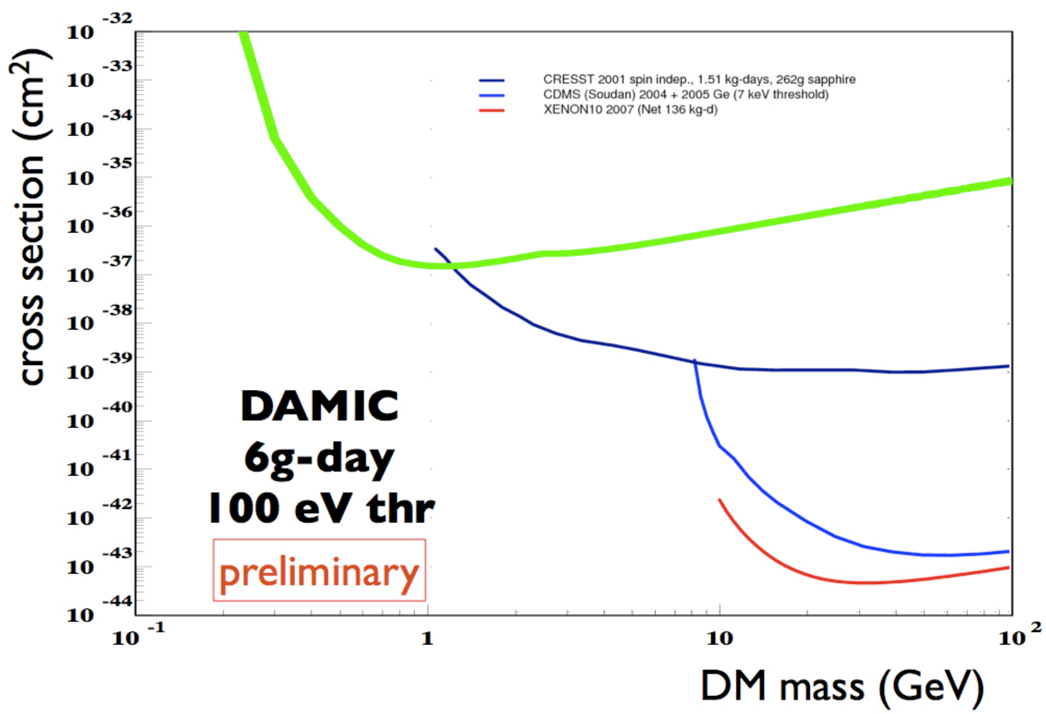
- Competition is heating up, with Xenon-100 and WARP-140 beginning to operate.

- DUSEL proposals describe spectrum of future possibilities
  - DUSEL detectors will have target masses of >1 ton and no background.
  - Sensitivity likely to increase by 3-4 orders of magnitude over next decade, exploring much of parameter space for dark matter in MSSM.
  - Intense competition between technologies; hard to pick a winner at this stage.
  - It seems that Fermilab has much to contribute regardless of technology choice.

EXTRA SLIDES

Low-Mass WIMP Search With CCDs

J. Estrada et. al, Arxiv 0802.2872



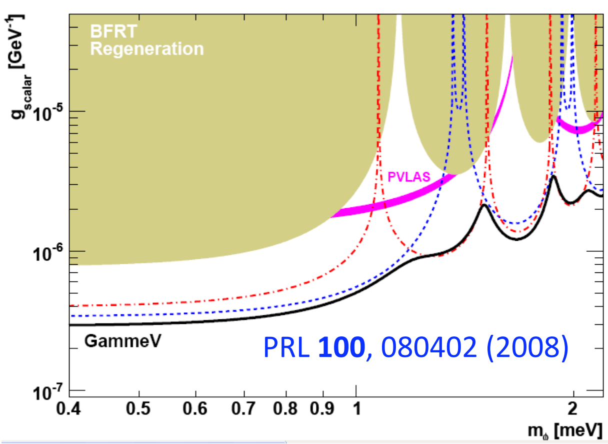
Low mass reach possible thanks to very low readout noise in DECam CCD detectors.

Small-scale laser experiment using accelerator magnets to search for dark particles

gammev.fnal.gov

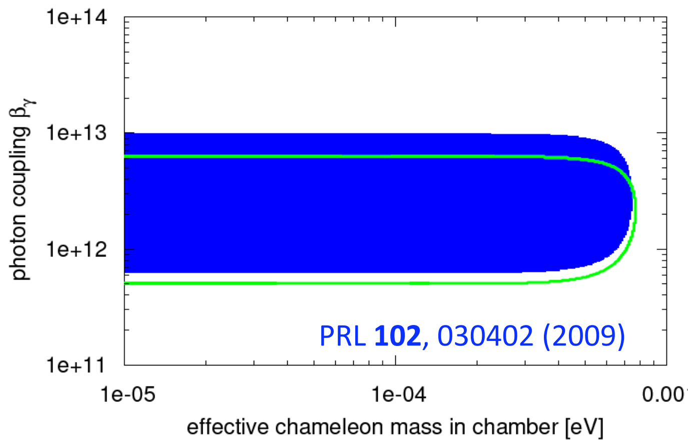
Light shining through a wall

excludes axion-like particles



Particle trapped in a jar

excludes “chameleons”



Future initiatives w/lasers+magnets:

2nd search for chameleons

Optical cavity technique for LSW